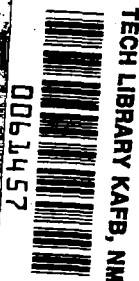


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FLIGHT EVALUATION OF TWO-SEGMENT APPROACHES USING AREA NAVIGATION GUIDANCE EQUIPMENT

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16. Abstract United Airlines, under contract with NASA Ames Research Center, has developed and evaluated a two-segment noise abatement approach procedure for use on DC-8-61 aircraft in air carrier service. The approach profile and procedures were developed in a flight simulator. Full guidance is provided throughout the approach by a Collins Radio Company three-dimensional area navigation (RNAV) system which was modified to provide the two-segment approach capabilities. Modifications to the basic RNAV software included safety protection logic considered necessary for an operationally acceptable two-segment system. With an aircraft out of revenue service, the system was refined and extensively flight tested, and the profile and procedures were evaluated by representatives of the airlines, airframe manufacturers, the Air Line Pilots Association, and the Federal Aviation Administration. The system was determined to be safe and operationally acceptable. It was then placed into scheduled airline service for an evaluation during which 180 approaches were flown by 48 airline pilots. The approach was determined to be compatible with the airline operational environment, although operation of the RNAV system in the existing terminal area air traffic control environment was difficult.					
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by: G.K. Schwind, J.A. Morrison
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SUMMARY

The operational evaluation of the guided two-segment approach in the DC-8-61 has shown that it is a safe and operationally acceptable flight procedure for routine air carrier service. It is suitable for use in both visual and instrument weather conditions and results in noise reductions.

The equipment used in this evaluation was a Collins ANS-70A, which is a certified ARINC Mark II area navigation (RNAV) system. It was programmed to provide two-segment approach guidance. This evaluation demonstrated that the two-segment capability can be added to an RNAV system at nominal cost because it does not require significant modification to the RNAV hardware or aircraft interface. An RNAV system which interfaces with existing Instrument Landing Systems (ILS) can provide an approach (RNAV/ILS) with accuracies comparable to conventional precision approach systems. It can also provide vertical and lateral guidance to non-instrumented runways (RNAV/RNAV approaches) with accuracies generally comparable to current non-precision approaches.

The profile developed for the DC-8-61 is a 5.5° upper segment which intersects the ILS glide slope (or 3° RNAV generated lower segment) at 575 feet above field level. The equipment provides guidance through the existing autopilot and flight director. Ninety-three pilots from the major sectors of the air carrier industry flew 1091 RNAV two-segment approaches in this evaluation. Of this number, 41 United Airlines (UA) pilots and 7 UA flight managers completed 180 approaches in revenue service. The procedure is not recommended in icing or if the upper segment tailwind component exceeds 15 knots. Instrument scanning and interpretation requirements are increased slightly, but this increase is not sufficient to impact safety.

The development of an acceptable procedure for the DC-8-61 indicates that the two-segment approach concept can be safely applied to aerodynamically clean jet transports using upper segment angles which will yield noise relief. The detailed research and operational development of the profile variables and flight procedures have been completed. There was a high degree of correlation between simulator and aircraft results.

The RNAV two-segment approach is compatible with the Air Traffic Control environment if it is properly coordinated with the approach controllers. The present approach vectoring and controller ordered descents are not compatible with the programmed point-to-point vertical and lateral flight plan requirements of RNAV.

INTRODUCTION

Background

The development of technical means to reduce community noise due to aircraft operations in the terminal area is being conducted in two general fields: modifications of terminal area operating procedures, and engine and nacelle modifications. Intensive studies are being made to assess the economic impact of engine and nacelle modification on the air carriers. Concurrent with this effort has been the development of two-segment approach procedures and equipment.

In the two-segment approach, the aircraft is guided along a flight path angle ("upper segment") greater than the normal ILS glide slope angle. A transition is then made to the glide slope at some altitude above touchdown which allows stabilization on the glide slope prior to landing. The two-segment approach provides noise abatement both by keeping the aircraft higher above the ground and by allowing reduced engine settings to be used on the upper segment.

Early studies and flight tests using experimental equipment demonstrated the effectiveness of the two-segment approach as a noise abatement technique. (Refs. 1-5) NASA investigation of the applicability of the technique to the commercial air transportation industry began with a concept evaluation conducted in a B-720 aircraft. (Refs. 6 and 7) These tests demonstrated that a more extensive evaluation under actual operational conditions was warranted.

Accordingly, NASA developed a program which included flight evaluations conducted by United Airlines in Boeing 727-200 and McDonnell-Douglas DC-8-61 aircraft. These two aircraft types represent two major categories of narrow-bodied commercial transports. The B-727 was equipped with a special purpose two-segment approach computer developed by Collins Radio Co. to interface with existing aircraft avionics. The DC-8 was equipped with a Collins RNAV system modified to provide two-segment approach guidance.

The development and evaluation of the two-segment approach conducted in the B-727-200 in 1972-73 resulted in a procedure which is safe and operationally acceptable for that aircraft (Ref 8). The major aircraft manufacturers extrapolated the B-727 data to other aircraft in current commercial fleets. Their conclusions were that the two-segment concept could be adapted to other aircraft types although some would require upper segment angles lower than the 6° upper segment established for the B-727 (Refs 9-11).

Centerline and sideline noise measurements made during the B-727 program showed that the two-segment approach reduces the ground level noise under the approach path (Ref 12). Extrapolation of these results to other current commercial aircraft showed that noise reductions could be expected in all cases, and that the two-segment procedure yields the greatest noise reductions for the noisiest aircraft (Ref 13).

By the end of the B-727 evaluation, the special purpose system had been developed well beyond the prototype stage. It could be ready for general use with some product improvements and minor modifications; however it requires an ILS equipped runway with Distance Measuring Equipment (DME) collocated with the glide slope transmitter.

The DC-8-61/RNAV evaluation reported herein was conducted as a logical extension of the B-727 program. The DC-8-61 was selected for evaluation principally because it is aerodynamically clean (i.e., it has less drag in the landing configuration) and is therefore more difficult to adapt to the two-segment concept than the B-727. Its approach noise characteristics are representative of the older narrow-body, long range aircraft projected for continued air carrier service into the 1980s.

The decision to evaluate a two-segment approach capability in an RNAV system was based on several important industry considerations. Assuming that RNAV will replace the current airways route structure, it was important to determine whether an RNAV system installed for enroute navigation could be modified to use the ILS and have the accuracy and repeatability required to provide precision two-segment approach guidance to ILS equipped runways. It was also important to determine whether RNAV would provide the capability for approaches to non-instrumented runways by utilizing the radio navigation aids (navaids) existing in most terminal areas. Finally, a three-dimensional RNAV system would include many of the input and output interfaces required for a two-segment approach system; a two-segment approach capability could therefore be added to an existing RNAV system which interfaces with the ILS at much less cost than installing an independent special purpose system.

Program Objectives and Major Tasks

The objective of the DC-8-61 program was to develop and evaluate an RNAV guided two-segment approach which is safe and operationally acceptable for use in routine air carrier operations, and which reduces ground level noise. The major tasks of the NASA program were:

1. Define the pilot interface that would satisfy the operational criteria of safety and pilot acceptability.
2. Modify the RNAV system software and hardware to incorporate the two-segment guidance capability, and design the installation of the system in the aircraft.
3. Modify the flight simulator and emulate the RNAV operating logic in the simulator software.
4. Develop the profile and procedures in the flight simulator for a safe and pilot acceptable two-segment approach.
5. Install the RNAV system and verify its two-segment capabilities in the evaluation aircraft.

6. Verify the simulator results in the evaluation aircraft.
7. Obtain an FAA Supplemental Type Certificate (STC) to permit operation of the RNAV two-segment system in revenue service under FAR Part 121.
8. Conduct an out-of-service guest pilot evaluation of the profile and procedures.
9. Conduct a six month in-revenue service line pilot evaluation of the profile and procedures.
10. Measure ground level noise to quantify reductions resulting from the two-segment procedure.
11. Document the program results in appropriate reports and in a 16-mm sound, color movie.

Modifications of the RNAV system and product support throughout the evaluation were provided by Collins Radio Company. Noise measurements were made by Hydrospace-Challenger, Inc. Both of these efforts were conducted under separate contracts with NASA (Refs. 14 and 15).

This program addressed all known industry operational concerns. The evaluation did not involve any economic or cost-benefit aspects of implementation other than estimating the cost to retrofit a two-segment approach capability into a specific aircraft type.

Program Description

The DC-8-61 program was structured to take maximum advantage of the findings and experience gained in the B-727 evaluation. Overall program policy direction came from UA's Flight Operations Administration through its Vice President of Flight Technical Services, Captain Howard Mayes. The key operational criteria which influenced the development of the approach came from Captain Gordon Brown, Manager of Flight Operations Development for the DC-8.

The same full time staff that had been involved in the B-727 program was involved in this program. This provided continuity in both the management and operations development of the programs.

The major program tasks were accomplished in 5 phases. Each phase involved tasks which logically followed from the work accomplished in the preceding phase. The program phases were:

- System Interface Definition and Design
- Engineering Simulation Evaluation
- Engineering Flight Evaluation and System Certification
- Out-of-Service Guest Pilot Evaluation
- Six-Months In-Service Evaluation.

The operational and technical interfaces were developed through UA Flight Operations and Engineering liaison with Collins and NASA. UA Flight Operations established the guidelines for system operations, displays, and annunciations.

Interpretation of existing displays and failure warnings was to be exactly the same as if the system were not installed, and the capability to revert easily to standard navigation modes was required. Collins and UA Engineering designed the RNAV system and its interface with existing aircraft components to meet these guidelines.

The principal development of profile and procedures occurred during the Engineering Simulation Evaluation. The UA DC-8-61 flight simulator (with visual system) was modified to include the basic instrument displays and annunciations that would be installed in the evaluation aircraft. System and interface logic were emulated in simulator software. The project pilot team conducted an investigation into all of the principal profile variables. Each was precisely varied to determine operationally optimum values. Interdependent variables were then combined to insure that they resulted in a safe and acceptable profile which could be flown using flight procedures that were the same as or similar to Standard Operating Procedures. A comprehensive investigation of system failures and effects was made to insure that none resulted in any secondary effects not considered in the pre-simulation analysis.

The environmental variables (icing, wind, wind shear, and turbulence) and the aircraft variables (center of gravity, gross weight, engine failures, and certain flight control and guidance system failures) were investigated to determine if any of these factors would limit the use of two-segment procedure. This phase resulted in a profile and procedure which was to be evaluated in the aircraft for verification or modification as necessary. Results of the Engineering Simulation Evaluation are contained in Reference 16.

Extensive development and evaluation of the system, profile, and procedure occurred in the out-of-service Engineering Flight Evaluation. Problems encountered by the equipment contractor in software development led to delays in delivery of the software for the RNAV two-segment system. In order to keep the program as much on schedule as possible, the decision was made to conduct the evaluation in two phases.

In Phase I the RNAV hardware and special instrumentation were installed and checked. Since RNAV software was not available, special vertical profile software was developed which utilized the general-purpose capabilities of the RNAV digital computer. This permitted the project team to proceed with verification of the vertical profile and basic flight procedures developed in the simulator. Lateral guidance was provided by the normal ILS. The objectives of establishing the optimum vertical profile and safe, pilot acceptable flight procedures were accomplished in this phase. The results of Phase I are reported in Reference 17.

In Phase II the full RNAV two-segment software was tested, modified, and evaluated. The flight testing revealed several deficiencies in the software which required revision during the evaluation. In addition, the procedures to initiate use of the RNAV just prior to the approach were developed, and the effects of various aircraft and ground system failures were evaluated.

The Federal Aviation Administration (FAA) Western Region conducted the STC flight tests immediately prior to the Guest Pilot Evaluation. They also accompanied the project team on out-of-service flights to Vancouver, Seattle, Chicago and Newark to complete the STC tests and to verify the FAA-approved approaches developed for those airports. As a result, the FAA issued STC SA2865WE on 7 June 1974, authorizing in-service two-segment approach evaluation.

The Guest Pilot Evaluation was conducted to obtain the opinions of experienced pilots with varied backgrounds as to safety and pilot acceptability. The guest pilots were called upon to assess whether all known industry operational concerns had been adequately addressed. Thirty-one pilots representing ten carriers, the Air Line Pilots Association, the three major commercial airframe manufacturers, and the FAA participated in this evaluation. A list of the pilots is provided at the end of this report. These pilots flew a total of 180 two-segment approaches. Results of the Phase II Engineering and Guest Pilot Evaluations are reported in Reference 18.

The In-Service Evaluation was the final and most important phase of the program. All of the preceding effort had been directed at developing a safe and operationally acceptable procedure for evaluation by line pilots in their day-to-day environment. Valid conclusions regarding the true operational viability of the procedure could be drawn only after it was subjected to this environment.

A captain who was scheduled to have three or more approach opportunities in the evaluation aircraft in a month was brought to the UA Training Center at Denver, Colorado for RNAV familiarization and two-segment approach training. His RNAV familiarization was substantially less than would be required for full RNAV qualification on this equipment.

During the In-Service Evaluation an RNAV technician who was thoroughly trained in the operation of the RNAV system was aboard as an observer and to assist as requested by the captain. He also managed the flight data recorder system and administered the captain questionnaire after each two-segment approach.

The In-Service Evaluation was conducted under guidelines established in the out-of-service evaluation. Weather minimums established for the approaches were at least 500 feet ceiling and one mile visibility (500-1) for RNAV/ILS and 800-2 for RNAV/RNAV. The approach was not permitted in icing or if tailwinds exceeds 15 knots.

A summary of the number of two-segment approaches made during the program is provided at the end of this report.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The two-segment approach profile and flight procedures for the DC-8-61 aircraft have been developed. An upper segment angle of 5.5° is compatible with the DC-8-61 performance characteristics. The upper segment should be intercepted above 3500 feet Above Field Level (AFL) to allow time to become stabilized on the upper segment prior to transition to glide slope or lower segment. The transition from the upper segment to the glide slope should allow stabilization by 500 feet AFL. Compared to a stabilized approach on a 2.9° glide slope, a 9-12 EPNdB reduction in centerline noise was measured beyond 3 n. mi. from touchdown under the two-segment approach (Ref 15).

The DC-8-61 RNAV two-segment approach was evaluated in the airline operational environment and found to be compatible with that environment. The approach is safe and requires no unusual pilot skills.

The use of RNAV in the existing ATC terminal area environment was difficult. If the ATC environment were fully adapted to aircraft operating with RNAV, and if the flight crews were fully familiar with operating the RNAV system in this environment, the addition of a two-segment approach capability to RNAV would not have a significant impact on cockpit workload.

Above-surface tailwinds in excess of 15 knots would make the 5.5° approach unacceptable because idle thrust would be required to prevent airspeed from increasing. The engine power required to track the 5.5° upper segment is well above idle thrust in normal approach conditions, but may be too low to assure anti-ice capabilities.

The two-segment approach is more than the RNAV vertical and lateral waypoints defining the profile; the system must be able to provide special approach event sequencing and safety protection logic unique to the two-segment approach. A three-dimensional RNAV system has been modified to provide guidance for two-segment approaches. The equipment contractor has indicated that other area navigation systems should be capable of providing the same type of guidance.

Instrument Landing Systems (ILS) inputs can be used by the RNAV system to provide a precision RNAV/ILS approach which could eventually be satisfactory to Category II weather minimums.

The RNAV system can also provide guidance for non-precision two-segment approaches using VOR-DME navigation to runways without an ILS. The vertical guidance and distance-to-touchdown information provided by a

three-dimensional RNAV system on RNAV/RNAV approaches is an advantage over existing non-precision procedures. The lateral accuracy of these approaches is not satisfactory for parallel runway operations. Weather minimums for RNAV/RNAV approaches will have to be established based upon the type, location, and quality of navaids available at a given runway because of their effect on lateral approach accuracy. Certain airports may not have satisfactory navaid coverage to allow RNAV/RNAV or RNAV/ILS approaches.

The results of this program, together with those of the B-727 program, show that the electronically guided two-segment approach is an operationally viable means of providing noise abatement. When full guidance is available throughout the approach it is acceptable to the pilot. The systems which were evaluated provided adequate protection from unsafe guidance.

Adding the two-segment approach capability to an RNAV system which is installed for other purposes would be significantly less expensive for both the aircraft operators and the Government than adding special purpose two-segment approach systems. In addition RNAV could provide noise abatement approaches at many more locations than special purpose systems.

Recommendations

If the two-segment approach capability becomes a requirement, such a requirement should be delayed until area navigation systems are in widespread use because of the cost and benefit considerations mentioned above.

RNAV systems designed to operate in the terminal area environment should facilitate responses to ATC requests without an increase in cockpit workload. Three-dimensional RNAV systems should maintain independence between vertical and lateral navigation and guidance functions to allow initiation of a two-segment approach profile independent of lateral position or flight plan to the runway.

Evaluation of any phase of operation with an RNAV system should be made with a system which is operational for all phases of flight. This would alleviate the biases which may be introduced by artificialities necessary to transition from conventional to area navigation operations.

RNAV accuracy should be considered in the specification of RNAV two-segment profile geometry, whether or not the approach interfaces with an ILS. The upper segment intersected the glide slope at 575 feet AFL to allow consistent stabilization on the lower segment by 500 feet AFL. However, this stabilization criteria would not be met if the upper segment is shifted towards the runway due to RNAV inaccuracies. In any future implementation of two-segment approaches the placement of the upper segment should be such that stabilization is attained at the desired altitude regardless of expected RNAV along track errors.

FAA certification of the RNAV system and approval of RNAV procedures in this program required that an FAA specified VOR and DME be tuned by the system to assure a minimum standard of accuracy. If the primary navaid is inoperative (as LAX was during two months of this evaluation), this requirement necessitates recertification of the affected approaches based on a different navaid. This situation is not satisfactory, and does not take advantage of the capability of some RNAV systems to determine the best possible combinations of available navaids to provide navigation. Certification of RNAV equipment and approval of RNAV procedures should be based on accuracy of navigation rather than on primary navaid requirements. However approach accuracy requirements may dictate specifying a group of acceptable navaids for approach navigation.

If the results of this program are extrapolated to other aircraft types, acceptable profiles and procedures could be satisfactorily developed and verified in certified flight simulators.

EQUIPMENT DESCRIPTION

RNAV System Installation

The avionics system installed in the DC-8-61 to provide two-segment guidance was a version of the Collins ANS-70A RNAV system. The ANS-70A is an ARINC 582 (Mark II)* system which uses a general purpose digital computer to provide automatic navigation along a complete vertical and lateral flight plan. The system automatically tunes the navigation radios according to certain range and geometry criteria. It statistically filters and combines radio, magnetic heading, and air data to navigate over a flight plan which is entered by the flight crew through a Control Display Unit (CDU). In addition to flight plan navigation, the system can provide a complete array of flight performance data such as winds, ground speed, and time to waypoint. The Collins Operator's Guide (Ref. 19) describes the basic ANS-70A system capabilities and operation.

The RNAV system interfaced with only the captain's displays and sensors. Certain modifications and additions to the existing aircraft equipment complement were made to provide the RNAV system with the necessary inputs. The VOR receiver was modified to provide sine and cosine station bearing outputs for use by the RNAV computer. The existing ARINC 521 DME interrogator was replaced with an ARINC 568 DME to permit the RNAV computer to tune it with ARINC 2X5 control lines and to provide a distance input in the pulsed pair format compatible with the RNAV computer. An additional ARINC 568 DME interrogator was installed to enable the RNAV system to obtain DME-DME position fixes. The existing air data system provided true airspeed, indicated airspeed, and pressure altitude referenced to 29.92 in. Hg to the RNAV computer. The captain's altimeter was replaced with one which provided the baro-correction setting to the RNAV computer. An independent ILS receiver was added to provide the localizer and glide slope inputs since the existing VOR-ILS navigation receiver operated in the VOR mode during RNAV operations. This additional ILS receiver also provided glide slope data in the non-RNAV mode.

Modifications and additions were also necessary to cockpit equipment to provide RNAV and two-segment approach displays (Figure 1). The captain's Horizontal Situation Indicator (HSI) was replaced with a unit which had two distance displays, one for RNAV computed distance-to-waypoint and one for standard DME. The course knob on this special HSI also served as the master RNAV engage switch. An RNAV mode position was added to the captain's flight director mode selector, and the existing AUX NAV position on the autopilot controller was activated for selection of the RNAV mode on the autopilot. The

*ARINC - Aeronautical Radio, Inc. - ARINC characteristics are the means by which the aviation industry provides various standards for airborne equipment. One deviation from the ARINC 582 standard was required to install the system in the DC-8-61; the CDU case had to be redesigned to fit in the forward pedestal location shown in Figure 1.

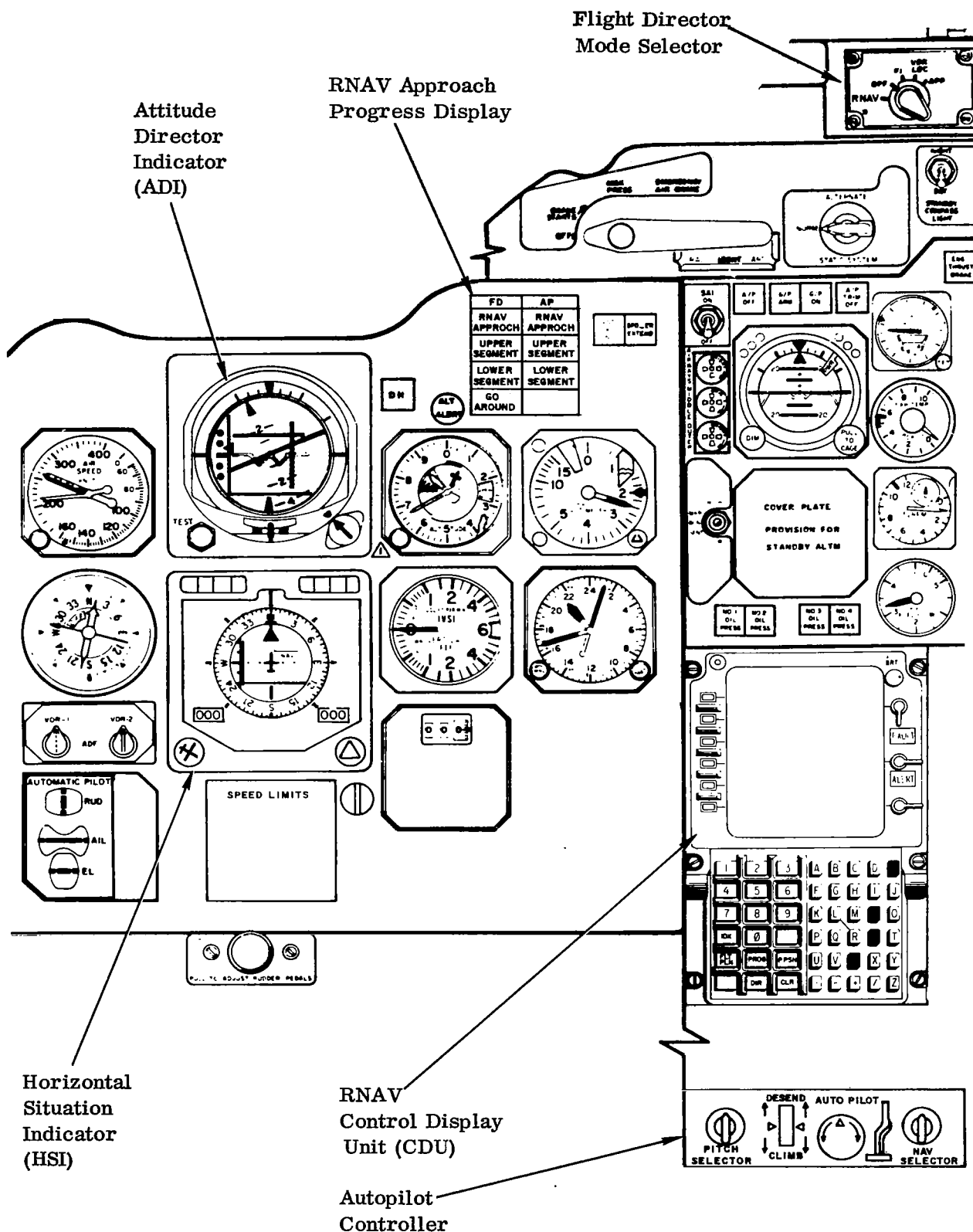


Figure 1 - Captain's Instrument Panel

captains Attitude Director Indicator (ADI) was replaced with a unit which included glide slope and expanded localizer deviation displays. An approach progress display was added to provide visual indication of proper mode selection on the flight director and autopilot and of the flight progress during two-segment approach operations. Autothrottles were installed for the out-of-service flight evaluations; they were found to be unnecessary for the two-segment approach and were not used during the In-Service Evaluation.

Three on-board data systems were used during the evaluation. A video tape system was used during the out-of-service flight evaluations to record cockpit instrument performance and to provide a voice recording. It was an excellent means of verifying system performance and observer comments and for detailed analysis of failures and abnormal operations. A digital flight recording system which utilized existing airline-type equipment was installed to record 90 aircraft, equipment, and crew performance parameters whenever an RNAV approach was being flown. This system provided data for analysis of specific approaches throughout the program, and for statistical evaluation of performance on the approaches flown during the In-Service Evaluation. An analog recorder provided instantaneous on-board data during the out-of-service flight evaluations.

Emulated Vertical Profile Computer System

In Phase I of the Engineering Evaluation the ANS-70A hardware was installed and the basic system interface was tested and verified. Then, utilizing the RNAV digital computer as a general purpose computer, the system was programmed to provide vertical two-segment approach guidance only to runways equipped with an ILS and a DME transmitter collocated with the glide slope transmitter. Upper segment vertical guidance was based on data from the collocated DME and aircraft barometric altitude. Standard aircraft localizer tracking systems provided lateral guidance for the approach.

System operation was functionally similar to the B-727 system. The two-segment approach was selected and the airport elevation was entered through the CDU. In addition, profile variables (upper segment angle and glide slope intersect altitude) could be changed through CDU to permit verification of results from the Simulation Evaluation. Instrument displays for the approach were the same as were planned for the RNAV two-segment approach except that the distance-to-touchdown information was raw DME data displayed in the upper right window of the HSI rather than Distance-to-Waypoint data in the upper left window.

RNAV Two-Segment System

Although the basic ANS-70A RNAV system is capable of navigation over an entire flight plan from origin to destination, in this evaluation it was certified for use in revenue service only for certain terminal area and two-segment approach operations. Numerous modifications to the basic ANS-70A navigation input-output, and logic functions were necessary to adapt it for use in the two-segment approach evaluation.

The primary change to the navigation functions of the system was the use of ILS inputs. ARINC 582 (Mark II) and 583 (Mark 13) RNAV characteristics both reserve pins for ILS augmentation. Attempts to optimize a combination of localizer and RNAV data for lateral navigation during the out-of-service evaluations were unsuccessful. The system was therefore modified to switch lateral control to standard localizer tracking systems when it was useable; so the localizer provided all lateral guidance after it was captured. Upper segment vertical guidance was based on RNAV calculations. Glide slope was used by the RNAV system to provide lower segment guidance on RNAV/ILS approaches. The RNAV system was also modified to provide approach guidance to non-instrumented runways by using area navigation alone. Although the addition of the RNAV/RNAV capability did not require changes to the navigation functions of the basic system, it required most of the same output and logic function changes as were required for the RNAV/ILS approach capability.

Most of the input-output changes to ANS-70A were associated with its interface with the existing aircraft equipment complement or to meet UA operational requirements. When the RNAV system is engaged, by pushing in the course knob on the captain's HSI, the following occur:

1. The frequency control of the captain's VOR and DME radios is transferred from the manual frequency selector to the RNAV system. This is annunciated by the illumination of a "VOR #1 AUTO-TUNED" light, since the frequency shown on the selector may not be the frequency which is being auto-tuned. The ILS receiver is still manually tuned with this selector.
2. The deviation displays on the HSI indicate vertical and lateral deviation from the RNAV flight plan entered on the CDU. This is annunciated by a mode indicator in the HSI which changes from RAD (radio) to RNV (area navigation). Guidance to follow the RNAV flight plan is available through the flight director or autopilot by selecting their respective RNAV modes.
3. The DME display on the captain's HSI is blanked out and the Distance-to-Waypoint display is activated.
4. The HSI course arrow is driven by the RNAV system to indicate the course to the next waypoint.

The primary input-output changes related to adding the two-segment approach mode to the RNAV were those required to accept ILS inputs and to provide outputs to the approach progress display. Modifications to the basic RNAV logic were also required for two-segment operations. Special rules were added for handling waypoints which defined approaches, such that two-segment approach waypoints in the flight plan could not be altered by the crew. In order to meet an FAA requirement, a primary VOR-DME station was specified for each approach to assure a minimum standard of approach accuracy. An approach event sequence system was required within the logic to provide progress annunciation and to arm the safety protection logic at the appropriate points in the approach.

The safety protection logic included in the two-segment mode of the RNAV was patterned on that developed in the B-727 program. The autopilot is disengaged, the flight director command bars are biased out of view, and the approach progress display is extinguished if the aircraft passes below the glide slope without capturing it, or if the capture does not occur by 550 feet above touchdown or .1 n. mi. beyond "Lower". * RNAV/ILS guidance will only be provided if the ILS frequency is tuned prior to "Upper" and the guidance will be removed if the ILS data is invalid while the aircraft is on the upper segment. The system is not armed for glide slope capture until the aircraft is less than 5 n. mi. from touchdown to avoid capturing false glide slope lobes. Prior to this glide slope arming point, upper segment guidance will be removed if the aircraft is below glide slope for more than ten seconds. The system monitors localizer performance and removes the guidance if the deviation is more than 2 dots after lateral control has been transferred to standard localizer tracking systems. The guidance is also removed if heading, airspeed, altitude, or baro-correction inputs are invalid or if the primary VOR or DME is invalid for more than 15 seconds. After the glide slope is captured, the primary VOR or DME signals are no longer required since navigation for the remainder of the approach is based on the ILS glide slope and localizer.

The RNAV system was successfully modified to provide two-segment approach guidance. The development of these modifications made it clear that the approach is more than the RNAV vertical and lateral waypoints defining the profile. The system must be able to provide special approach event sequencing and safety protection logic unique to the two-segment approach. This program also demonstrated the successful use of ILS signals in an RNAV system. However, it was concluded that when localizer signals are available for approach guidance, they should be used for steering directly rather than as an input to the RNAV position estimate software.

* Quotation marks (" ") are used in this report to identify names of RNAV waypoint.

APPROACH PROFILE AND PROCEDURES

Profile and Procedure Development

The two-segment approach profile and procedures were developed in a DC-8-61 flight simulator at the UA Flight Training Center. Nearly 1500 approaches were flown during 135 simulator flying hours. The factors affecting the profile or procedure were studied in the simulator under exact and repeatable conditions. The external variables, profile variables, and procedural variations were investigated for their effect on safety, repeatability, pilot workload, and ground level noise while other parameters were held constant.

The simulator was modified to include instruments and displays the same or similar to those which were to be installed on the aircraft. It was also equipped with two data systems, an analog recorder for performance analysis and comparison with project pilot findings, and a profile and ground level noise plotter. Although the noise level plotter was not designed to yield accurate noise predictions for correlation with actual measurements, it provided estimates of the noise differences between different approach profiles.

The DC-8 Simulation Evaluation utilized the experience gained in the B-727 program to the maximum extent possible. Because the effects of certain factors on the two-segment approach had been thoroughly evaluated in the B-727 program, the DC-8 program was designed primarily to verify or modify the previous results to accommodate the differences between the DC-8-61 and the B-727-200 aircraft.

The profile and approach procedures resulting from the Simulation Evaluation were verified in the Phase I Engineering Flight Evaluation. There was a high degree of correlation between simulator and aircraft results, and the same profile and procedures were used throughout the Phase II Flight Evaluation, Guest Pilot Evaluation, and In-Service Evaluation.

DC-8 Two-Segment Approach Profile

The profile developed (Figure 2) consists of a 5.5° upper segment which intersects the ILS glide slope (or 3° computer-generated lower segment for RNAV/RNAV approaches) at 575 ft Above Field Level (AFL). "Upper is nominally 3500-4500 ft AFL and 7-8 n. mi. from touchdown. The transitions from the initial approach altitude to the upper segment and from the upper segment to the glide slope or lower segment are initiated at capture points which are determined by rate of closure on the next waypoint and displacement from it. This rate sensitive capture assures that the transitions are completed without overshoots or undershoots of the desired flight path regardless of air-speed or winds. The transitions are smooth and slow enough to assure that g-force sensations are no greater than those caused by normal terminal area maneuvers.

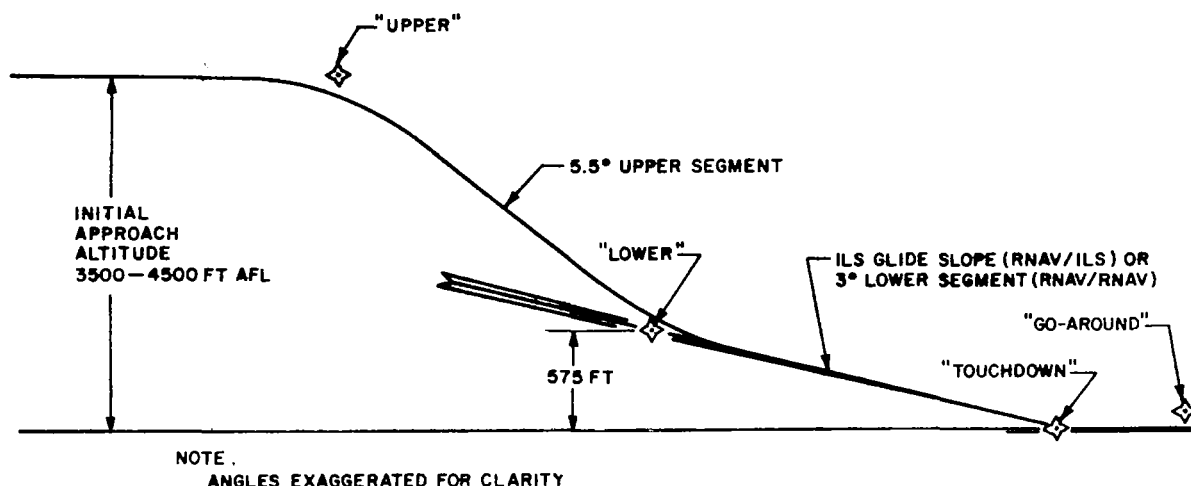


Figure 2 - RNAV Two-Segment Approach Profile for DC-8-61 Aircraft

The initial approach altitude was based on several operational and technical considerations. It was determined that the minimum altitude for "Upper" which provided an upper segment long enough to permit stabilization on speed and flight path prior to the lower transition was 3500 ft AFL. Higher altitudes provide additional noise abatement and a longer stabilization period on the upper segment. However, altitudes for "Upper" greater than 4500 ft AFL (about 8 1/2 n. mi. from touchdown) could result in delays and problems with ATC because the final approach course had to be intercepted prior to "Upper." This was due to the way in which the two-segment approach capability was implemented in the ANS-70A. The system required that "Upper" be at a fixed altitude (and therefore a fixed distance from touchdown) for any given approach, and that it be on the extended runway centerline. The evaluation experience indicates that this restriction unacceptably limits the flexibility of the procedure. A complete decoupling of the vertical and lateral navigation functions of the RNAV would be advantageous, as it would allow the initiation of a two-segment vertical profile without regard to the lateral approach flight plan.

Upper segment angles of 5° to 6.4° were evaluated in the simulator, although it was known that aerodynamic differences between the DC-8 and the B-727 would require that the acceptable angle for the DC-8 would be less than the 6° angle used on the B-727. High angles provide more noise abatement, but operational considerations dictated that the angle be shallow enough to allow airspeed stabilization with the engines above idle thrust in tailwinds up to 15 knots. The maximum angle which met these criteria was 5.5°.

The altitude of "Lower" was also based on the operational and noise abatement considerations. Lower altitudes for "Lower" provide more noise abatement because they result in the upper segment being closer to the runway, and therefore higher above the ground at any given point on the upper segment. The minimum operationally acceptable altitude for stabilization on the glide slope based on UA policy was 500 ft AFL. In the DC-8-61 it was determined that this criterion could be consistently met if the altitude of "Lower" were 575 feet AFL.

Both the upper and lower transitions are faster in the DC-8 than they were in the B-727. The engines on the DC-8 are under the wing, below the pitch axis of the aircraft. This results in a pitch down moment when the throttles are retarded and a pitch up moment when power is added, thereby assisting the pitch maneuvers required to transition from one flight path angle to another.

Under a separate contract to NASA, Hydrospace - Challenger, Inc. of San Diego took noise measurements at Stockton during the Engineering Flight Evaluation. Noise measurements were made of 8 ILS and 15 two-segment approaches by the aircraft, which was equipped with JT3D-3B engines. These measurements were used to compare the ground level noise for a stabilized 2.9° glide slope approach with a two-segment approach under the same conditions (Ref. 15). Results indicate that the two-segment procedure provides noise reductions under the approach path centerline of 9-12 EPNdB outside of 3 n. mi. from touchdown.

Two-Segment Approach Procedure

The RNAV system is programmed for a two-segment approach when the crew enters the appropriate set of approach waypoints into the RNAV flight plan. The set of four waypoints, "Upper", "Lower", "Touchdown", and "Go-Around", are entered as a group. Deletion of any one of the waypoints in the group will cause the entire set to be deleted from the flight plan. The altitudes of and courses between these waypoints cannot be changed by the crew as they can be for enroute RNAV waypoints. The programmed altitude for "Upper" and "Lower" are the same as those shown on the pilot's approach reference chart for the specific approach (e. g. Figure 3).

When the distance to "Touchdown" along the RNAV flight plan is less than 30 nautical miles, the RNAV APPROACH annunciators on the approach progress display are illuminated amber if the RNAV system is engaged and RNAV is selected on the flight director mode selector or AUX NAV is selected on the autopilot controller. When the distance to "Upper" is less than 15 nautical miles, the RNAV APPROACH annunciator illuminates green. During the out-of-service flying a "tune ILS frequency" reminder on the CDU was evaluated, since the RNAV system did not auto-tune the ILS. This was later deleted because acknowledgement of the message was an added workload item and did not assure that the ILS receiver was tuned. Any future implementation of two-segment or standard ILS approaches in an RNAV system could either incorporate such a reminder and have it cancelled automatically when the ILS frequency is tuned, or could include auto-tuning of the ILS receiver by the RNAV system.

Eight n.mi. from "Upper", the UPPER SEGMENT annunciator is illuminated amber and the HSI vertical deviation is switched to display deviation from the upper segment. This is the point at which the system requires the primary VOR and DME radios to be tuned and valid in order for the approach to continue. From this point until "Touchdown" is passed, the lateral and vertical deviations from the two-segment profile are displayed with scale sensitivities corresponding to those of nominal ILS facilities for both RNAV/RNAV and RNAV/ILS approaches.

Because of the aerodynamic cleanliness and drag programming constraints of the DC-8-61, the approach entry airspeed and aircraft configuration are important in flying a stabilized approach. The optimum entry and approach procedures established are shown in Figure 4. As the airplane flies toward "Upper" in the maneuvering configuration, with flaps at 15° or 25°, the HSI vertical deviation bar moves into view indicating that the aircraft is approaching the upper segment. The landing gear should be extended at this point. The upper segment deviation bar provides

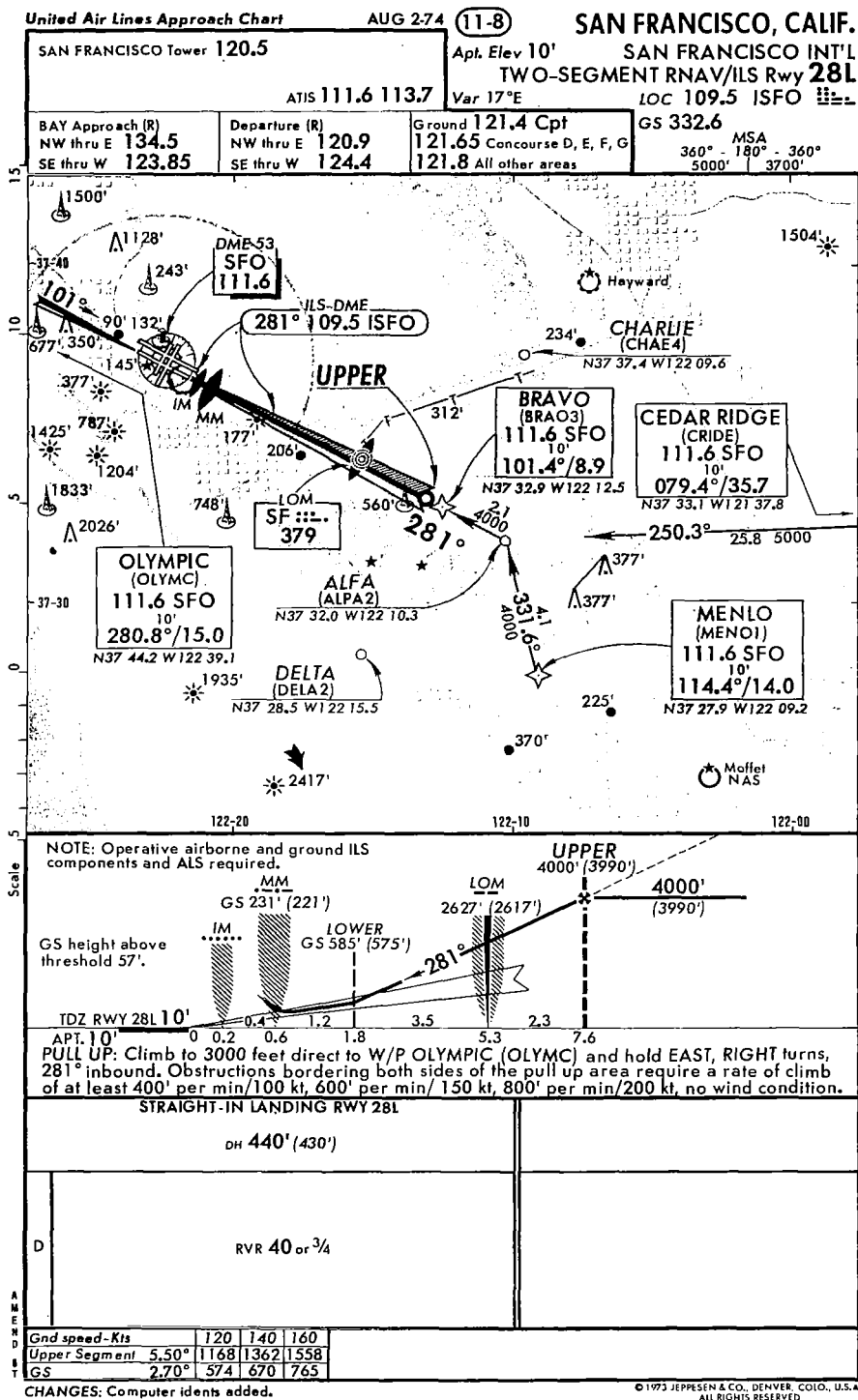


Figure 3
Typical RNAV Two-Segment Approach Reference Chart
 (For illustration only - Not to be used for Navigation Purposes)
 Reprinted by Permission

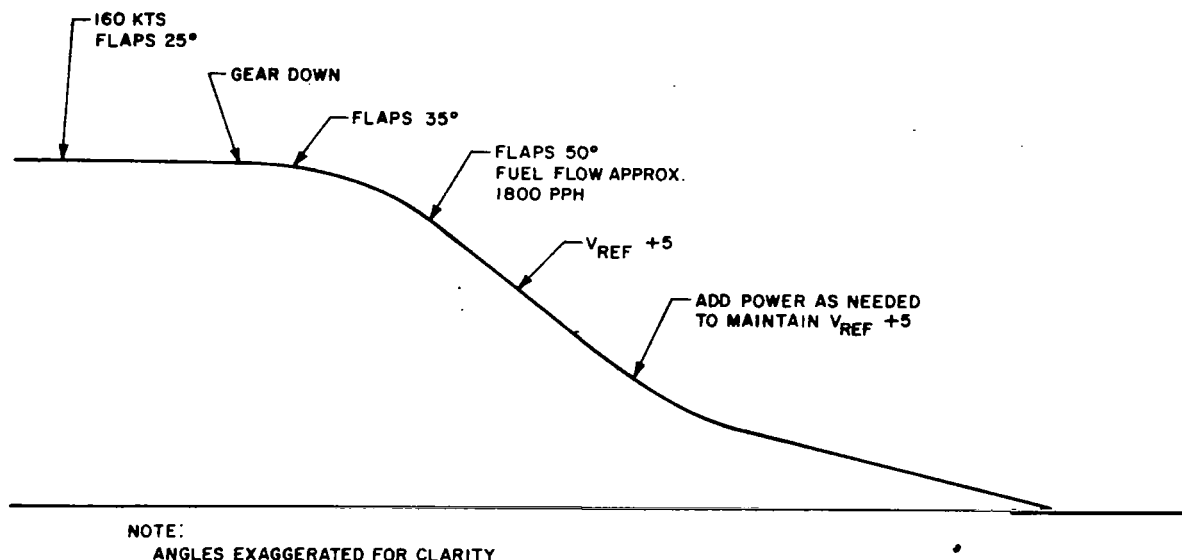


Figure 4 - DC-8-61 Two-Segment Approach Procedures

a cue for a configuration change which is similar to the cue provided by glide slope deviation on a standard ILS approach. When the upper segment capture point is reached, the UPPER SEGMENT annunciator is illuminated green and guidance is provided to transition to the upper segment. The transition is smooth, and is aided by the natural pitch down of the aircraft when the throttles are retarded. When "Upper" is passed, the distance-to-waypoint display provides distance to "Touchdown" since this is the distance of interest to the crew during the approach, even though the guidance at this point is being provided to "Lower". The fuel flow is set at approximately 1800 pounds per hour (pph) in order to stabilize on $V_{ref} + 5$ knots airspeed on the upper segment. Full (50°) flaps are also selected at this point. On RNAV/ILS approaches the correct positioning of the upper segment is verified by the standard procedure of checking the altitude at which the aircraft passes the outer marker with that altitude published on the approach reference chart.

The LOWER SEGMENT annunciator illuminates amber when the distance to "touchdown" is five nautical miles. At the lower capture point the LOWER SEGMENT annunciator is illuminated green and guidance is provided to transition to the lower segment, or to the glide slope on RNAV/ILS approaches. The transition is aided by the natural pitch-up of the aircraft as thrust is added to maintain airspeed on the shallower lower segment.

After the lower transition has been initiated on an RNAV/RNAV approach the guidance is removed upon passing "Lower" as an indication to the crew that they should have visual contact with the runway. This is required because the RNAV/RNAV approach may lack the precision necessary to provide accurate guidance below 500 feet AFL.

OPERATIONAL RESULTS

Methodology

The B-727 and DC-8 programs were conducted to determine whether the concept of approach path modification for noise abatement which had been proven technically and operationally feasible in earlier studies could be translated into airborne guidance equipment and two-segment approach flight procedures which are safe, operationally acceptable, compatible with the ATC environment, and usable in instrument weather conditions to CAT II minimums.

The results reported herein are based on the analysis of inputs from guest pilots, line pilots, on-board RNAV technicians, and statistical analysis of recorded data. The primary sources of guest and line pilot opinion were their written responses to prepared questionnaires.

The emphasis in the guest pilot questionnaire was on the procedure and the cockpit guidance and displays. The questionnaire was usually administered to the guest pilots after their simulator training session and then again after their evaluation flight of six approaches. At the completion of the Guest Pilot Evaluation the questionnaires were carefully analyzed and conclusions were drawn. Before these conclusions were considered valid they were sent to all of the guest pilots for their review and comment. None of the pilots who responded questioned the conclusions.

The emphasis in the line pilot questionnaire, which the captain completed after each two-segment approach, was on the use of the procedure in his day-to-day revenue service environment. It contained specific operational detail about the procedure and the ATC interface. A detailed summary questionnaire was completed at the end of the evaluation by those line pilots who had flown six or more two-segment approaches in revenue service. This questionnaire was designed to yield information on certain key areas in which the pilots' opinions needed to be based on some minimum amount of exposure to the procedure. The minimum experience of six approaches was selected so the line pilot who completed this questionnaire had experience with the procedure at least equal to that of the guest pilots.

Thirty-one guest pilots flew a total of 180 two-segment approaches in their evaluation. Guest pilot results are based on responses from 19 simulator and 27 aircraft questionnaires. Forty-one UA line captains and 7 flight managers flew a total of 180 two-segment approaches in the six-month In-Service Evaluation. Eleven line captains with an average of over eight approaches each completed the line pilot summary questionnaire.

Safety

The overriding consideration in all of the two-segment approach development decisions was safety. The procedure could be pilot, industry and FAA-acceptable only if it was safe. All major factors were carefully considered and evaluated for their potential impact upon safety.

The first of these was the requirement for an approach profile which could be flown without requiring unusual piloting skills. All of the profile variables were thoroughly investigated in the flight simulator and verified in the evaluation aircraft to establish a profile which satisfied this requirement.

Two sources of information were used to assess whether unusual skills were required. The first is a section of the pilot questionnaire in which the pilots compared the two-segment approach cockpit activity with that same activity on other instrument approach procedures with which they are thoroughly familiar. The second source is the statistical analysis of recorded data which shows how well the pilots as a group flew the two-segment profile in the revenue service environment.

The table on the next page summarizes the comparisons of cockpit activity made by the guest pilots and by the line pilots who completed the summary questionnaire. From this summary it has been concluded that Instrument Interpretation and Instrument Scanning are the two areas of cockpit activity most significantly impacted by the two-segment approach procedure. No well-defined or common reason for this is cited either by the guest pilots or the line pilots, but the same areas were also identified by the B-727 guest pilots. None of the pilots who ranked any item significantly more difficult indicated at any point in his questionnaire that the item rendered the procedure unsafe or otherwise unacceptable.

Figure 10 on page 39 shows that on the average, the line pilots tracked the two-segment profile on flight director with deviations only slightly larger than the autopilot deviation. Since the profile was flown this well on flight director with only minor impact upon cockpit activity, it has been concluded that the two-segment procedure does not require unusual piloting skills.

The second major factor was the determination of any conditions under which the procedure would not be recommended.

Icing, tailwinds, turbulence, and wind shear were thoroughly investigated in the simulator. Strong tailwinds, turbulence, and wind shear were also experienced in the last part of the Engineering Flight Evaluation and Guest Pilot Evaluation which were conducted at Denver and Pueblo at a time of year when these conditions are prevalent. The effects of aircraft center of gravity at both the aft and forward limits, gross weights from minimum to maximum landing weights, and the irregular or emergency

PILOT RANKINGS OF MAJOR COCKPIT ACTIVITY
(Two-Segment vs Conventional)

Ranked Item	Compared to Conventional Approach, 2-Seg Approach Activity is						
		Unac- ceptable	Signif- icantly More Difficult	Slightly More Difficult	Not Different	Slightly More Easier	Signif- icantly Easier
Autopilot Usage	GP Line			8% 36%	92% 46%	9%	9%
Flight Director Following	GP Line			29% 18%	71% 73%	9%	
Instrument Interpretation	GP Line		4% 18%	35% 36%	61% 37%	9%	2%
Flight Progress Annunciation	GP Line		18%	17% 27%	83% 55%		
Instrument Scanning	GP Line		4% 27%	26% 45%	70% 19%	9%	
Airspeed Control	GP Line		9%	13% 36%	87% 55%		
Flap Management	GP Line		4%	9%	87% 100%		
Trim Control	GP Line			17% 18%	83% 82%		

Note: Figures represent percent of total pilots ranking the item.

GP = DC-8 Guest Pilots (31 pilots)
Line = DC-8 Line Pilots (11 pilots)

situations which influence the pilot's decision as to the type of approach he would select were investigated in the simulator.

As a result of these tests, it was concluded that the following conditions would make the use of the two-segment approach inappropriate:

1. Upper segment tailwind components greater than 15 knots, since the engines must be spooled down below the immediate thrust response level and the rate of descent necessary to track the upper segment is unacceptably high.
2. Conditions requiring full engine and airframe anti-icing, since the engine power required for tracking upper segment with a 15-knot tailwind is less than the manufacturer recommends.
3. Conditions requiring any irregular or emergency procedure in which the pilot is unable to obtain full flaps or in which selection of less than full flaps for landing is required, since the procedure was designed for full (50°) flaps.

The effect of the other environmental and aircraft factors tested was the same on the two-segment approach as on conventional instrument approach procedures.

Another major factor which has a direct impact on safety is the provisions made in the equipment and cockpit displays and annunciations which protect against unreliable guidance or failure to capture the glide slope. These are discussed on page 14. These were thoroughly tested in the Engineering Flight Evaluation and were demonstrated to the satisfaction of the FAA in the STC flights leading to system certification for evaluation in revenue service.

The table on the next page summarizes the guest and line pilot responses to the question of whether or not they consider the RNAV/ILS and RNAV/RNAV procedures safe.

GENERAL NATURE OF COMMENT	RNAV/ILS		RNAV/RNAV	
	GUEST PILOTS	LINE PILOTS	GUEST PILOTS	LINE PILOTS
Safe - No qualifying comment	41%	55%	24%	45%
Safe - With proper minimums	17%	-	34%	-
Safe - With adequate training	21%	-	6%	-
Safe - With tailwind and/or anti-ice restrictions	3%	18%	3%	10%
Safe - Lateral accuracy needs improvement	-	-	10%	27%
Safe - Equipment reliability needs improvement	3%	9%	6%	18%
Conditionally unsafe (see below)	15%	18%	17%	0%

Four guest pilots and two line pilots indicated that one or the other of the RNAV two-segment procedures was not acceptably safe under some specific condition or for some specific reason. A brief summary of each of these cases is provided below:

Guest Pilot - This pilot stated that the RNAV/ILS and RNAV/RNAV lower transitions commenced too low. He indicated that he was stabilized after the lower transition and recommended RNAV/ILS minimums of 400-1 and RNAV/RNAV minimums equal to ADF minimums. This pilot was unable to participate in a simulator training session prior to evaluation of the procedure in the aircraft.

Guest Pilot - This pilot stated that the lower stabilization point is too low in both procedures in adverse weather. He felt the aircraft should be stabilized as high as in the standard ILS. He did not recommend minimums on his aircraft questionnaire. He recommended ADF minimums for both procedures on his simulator questionnaire.

Guest Pilot - This pilot felt that the RNAV/ILS could be acceptably flown by most pilots, but he questioned its safety if flown by the least competent pilots. He felt that the two-segment approach degrades already-thin safety margins and recommended that minimums be at least 200 ft above the lower transition. (Another guest pilot expressed a similar concern after the In-Service Evaluation had been completed). He equated the RNAV/RNAV to the other non-precision procedures but stated that he felt any non-precision approach is unacceptable for jet aircraft. He recommended 800-2 for RNAV/ILS and VFR for RNAV/RNAV.

Guest Pilot - This pilot questioned RNAV/RNAV only. He felt that more testing of approaches to 500-700 ft is needed since the approaches were not consistent. He ranked RNAV/RNAV inferior to ADF and recommended 700-1000 ft minimums.

Line Pilot - This pilot indicated that RNAV system management required too much heads down in terminal area. This pilot also experienced an HSI vertical deviation bar failure in which the bar remained in view, which caused him to question the fail-safe operation of the system. This pilot recommended Category II minimums for RNAV/ILS and made no recommendation for RNAV/RNAV minimums due to lack of experience with the RNAV/RNAV procedure.

Line Pilot - This pilot stated that he did not consider the two-segment approach a stabilized approach. He cited the variation of speed, power, trim, and sink rate as simultaneous factors in the lower transition. He recommended RNAV/ILS minimums of 300-1 and RNAV/RNAV minimums of 400-1 and preferred VOR non-precision approaches over RNAV/RNAV approaches.

In follow-up correspondence two guest pilots expressed opposition to the concept of forcing the pilot community to adopt flight procedures for the sake of noise abatement. One other pilot indicated that he found no operational fault with the two-segment procedure, but that he felt that the minimum drag procedure would produce the same or greater noise benefits without appreciable cost or crew training.

The guest and line pilots were asked to recommend appropriate minimums for RNAV/ILS and RNAV/RNAV approaches. This was interpreted as an indication of the pilots' opinion regarding the overall safety of the procedure. The tables below summarize the ceiling recommendations.

RNAV/ILS

	CAT II	CAT I	CRNT ILS	200'	300'	500'	400- 600'	500- 1000'	NON- PREC.	VFR	NO REC.
GUEST PILOTS	7	1	1	2	1	-	3	1	1	2	10
LINE PILOTS	7	-	-	-	3	1	-	-	-	-	-

RNAV/RNAV

	300'	400'	500'	400- 600'	500- 1000'	NON PREC.	VOR/ ADF	CIRC.	VFR		NO REC.
GUEST PILOTS	-	-	-	6	4	3	5	2	2		7
LINE PILOTS	2	5	2	-	-	-	-	-	-		2

Pilot Acceptability

In planning both the guest pilot and line pilot evaluations, it was recognized that it would be difficult to have the pilots divorce their opinions of the two-segment procedure from their opinions of operating the RNAV system and/or of using a navigational concept with which they had little or no previous experience.

The guest pilots were given only a basic familiarization with the RNAV system. In all but a few cases, the project pilot who accompanied each guest pilot in the aircraft operated the RNAV system. This helped to channel the emphasis to the approach procedures and guidance and displays, however it tended to make the pilot feel disoriented, since he is accustomed to knowing where his navigation and guidance systems will be taking him.

In the In-Service Evaluation, basic familiarization with the RNAV system was provided to the pilot in his training at Denver. An RNAV technician who was well-trained on the system was aboard at all times to assist the captain with his operation of the system for the approach. In analyzing the line pilots approach and summary questionnaires it became clear that the factors related to the RNAV system operation had influenced their responses to questions which had been intended to address purely operational aspects of the two-segment procedure.

In drawing conclusions regarding pilot acceptance of the two-segment procedure, when a pilot's comments on a question alluded only to the RNAV system or some system-management problem and he was reticent on the operational aspects of the procedure, the interpretation was that the procedure itself was acceptable to him. The other important qualification applied in this analysis is that if a pilot stated that the procedure would be unacceptable under some specific conditions or circumstances, the interpretation was that he considered the procedure acceptable in the absence of these specific conditions.

The results of the Guest Pilot Evaluation indicated that the RNAV two-segment procedure would be pilot acceptable for normal line operations. The predominant qualification which the pilots attached was that proper training in the system and procedures would be necessary. A lesser concern was that conservative weather minimums should be established, at least initially, and that the reliability and accuracy of the RNAV system be improved. In recognition of these concerns, all pilots who participated in the In-Service Evaluation were given an FAA-approved simulator and RNAV familiarization course at UA's Flight Training Center in Denver. Weather minimums of 500-1 were established for RNAV/ILS approaches and 800-2 for RNAV/RNAV approaches. Equipment improvements and modifications were a continuing process throughout the evaluation.

As was explained earlier, it was felt that a line pilot should have at least the same number of two-segment approach attempts as the guest pilots had flown (6 approaches) in order to make a valid judgment as to the pilot acceptability of the RNAV two-segment procedure. The line pilot results relating to pilot acceptance are based on inputs from 11 line pilot summary questionnaires. The line pilots were asked to compare the relative advantages of the two-segment procedure and the existing "Keep 'em High" procedure used in visual conditions. A nearly unanimous opinion was that the vertical guidance and flight path standardization provided by the RNAV is superior to the VFR procedure. This opinion was also expressed by a number of the guest pilots, however the heads-down time required for RNAV system management was cited by about half of the line pilot group as a disadvantage.

A comparison was made between the RNAV/RNAV and other non-precision approach procedures in current use. The results of this comparison are summarized below:

DESCRIPTION OF RANKING	GUEST PILOTS	LINE PILOTS
RNAV/RNAV : Equal to or better than other non-precision approach procedures	52%	55%
Better than one or more of the current non-precisions	14%	9%
Equal to ADF	10%	27%
Inferior to ADF	3%	9%
No response to question	21%	-

Approximately half of the line pilots again indicated that the vertical descent guidance and distance to touchdown provided by the RNAV system are preferable to the unguided descent to Minimum Descent Altitude (MDA) and timing methods used in some of the current non-precision procedures. Several pilots indicated that the lateral accuracy of the RNAV/RNAV approach should be improved and lateral stand-off problem should be corrected. Lack of experience with RNAV and the inflexibility of the RNAV system in the current ATC environment were also cited as reasons for selecting other non-precision approaches in preference to RNAV/RNAV approaches.

A similar comparison was made between the RNAV/ILS approach and the ILS procedure. The pilots were asked to indicate which of the two they would select for an approach into weather reported as 400-1HK.(400 feet ceiling, 1 mile visibility in haze and smoke). Six selected the standard ILS, 3 selected the RNAV/ILS and 2 made no selection. The reasons given for preferring the standard ILS were lack of experience with RNAV (4 pilots) and inflexibility of RNAV system as compared to conventional navigation system (2 pilots). Most of the pilots indicated that they would require no more experience to be competent in the RNAV/ILS than they had required to become competent in the standard ILS when it was first introduced.

In response to the question regarding suggested changes which the line pilots would recommend to make the procedure more acceptable, 5 indicated that they recommended no change, 4 commented on equipment-related matters, 1 on training, and 1 inquired as to the feasibility of using RNAV for standard ILS in weather and the 5.5° two-segment in VFR. Several pilots indicated that they would have liked to be able to use the system for a greater portion of the flight than had been the case in this evaluation.

Terminal Area Operations

Figure 5 shows the approximate relationship between the B-727 and DC-8 profiles which were developed and evaluated in these programs. The upper segments of the two profiles cross at about 5 n. mi. from touchdown.

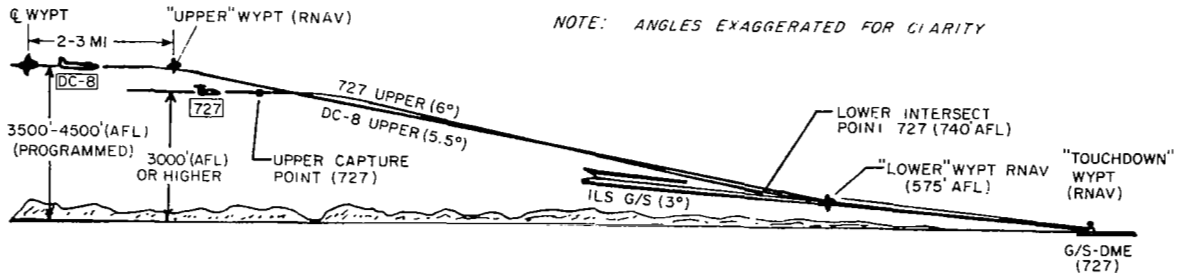


Figure 5 - Comparison of B-727 and DC-8 Two-Segment Approach Profiles

In the RNAV system used in this evaluation, the 3500-4500 ft AFL initial approach leg shown in Figure 5 was flown level and on the final approach course. This was necessary because the vertical and lateral axes were inter-dependant and required passage of "Upper" within narrow on-flight plan tolerances. This portion of the pre-approach flight plan also provided a wings-level segment on which to stabilize entry airspeed and to configure for the upper segment transition. Since the prime objective of this program was the evaluation of an RNAV-guided two-segment approach, this artificiality was designed to maximize the two-segment approach yield and to increase the objectivity of the pilots' evaluations of the approach procedure itself, by permitting them to establish near-ideal entry conditions prior to upper segment capture. It was recognized that this method of maneuvering for approach was not in consonance with the RNAV terminal environment planning currently under study by industry RNAV committees

The centerline waypoint outside of "Upper" not only established the pre-capture leg, but it also served to protect against system logic aborts which were being induced when the aircraft was vectored past "Upper" on a downwind leg which contained no waypoints between the aircraft and "Upper". These abort situations were resulting in one of two unacceptable conditions: Either the approach opportunity was lost, or the RNAV Technician had to re-program the approach waypoints into the flight plan. This had the undesirable side effects of a high level of activity on the CDU and of creating an understandable loss of pilot confidence and orientation at a very critical point in flight.

The use of the pre-"Upper" centerline waypoint helped avoid the logic abort problem; however it was found that the random ATC vectoring and descent commands in the terminal area are incompatible with the point-to-point lateral track and programmed vertical profile requirements of a three-dimensional RNAV system. In attempting to use RNAV for the limited purpose of making two-segment approaches, these incompatibilities were adversely affecting the objectivity of the evaluation of the two-segment procedure. The operationally-induced aborts and high RNAV Technician activity on the CDU appeared to be causing the pilots to associate these unrelated results with the procedure itself.

Consideration of the pilot comments, the RNAV Technician feedback, and the careful analysis of the recorded data suggest that, in anticipation of the use of RNAV for two-segment (or other) approaches, the following are needed:

1. Place the RNAV system into full operation enough in advance of commencing the approach to permit it to update its position estimate and compute current flight and navigational dynamics.
2. Program pre-approach maneuvering inside of a feeder waypoint via a point-to-point track with an associated vertical profile.
3. If terminal area traffic conditions require a departure from the routing which has been programmed, the pilot should be able to select a "standby" mode while maneuvering off of the plan, and then return to the plan when he is cleared by ATC to do so.

Given the above conditions, there is strong reason to expect that the pilot's RNAV orientation would be greatly improved, and his confidence in the guidance during the approach would be increased.

Through direct coordination with the cognizant FAA Flight Inspection Field Offices and with the local controllers in each terminal area, several FAA-approved area entry procedures which were compatible with local area routing and altitude restrictions were established. In the last two months of the In-Service Evaluation, these were used successfully at San Francisco, Los Angeles, Las Vegas, Milwaukee, Washington-Dulles, Windsor Locks-Bradley and Richmond. While this represents a limited experience, application of this concept had the beneficial results that had been expected.

Based on the operational use which was made of this system in the evaluation, it appears that it is essential to de-couple the lateral and vertical axis logic so that each can proceed with its own navigational functions independent of the other. This would permit intercepting a programmed vertical gradient such as the 5.5° upper segment at the altitude appropriate for the specific lateral

flight plan. This would also permit following a programmed lateral track independent of an ATC commanded descent profile. Properly mechanized, the RNAV system does not have any significant limitations in providing navigation along a programmed vertical and/or lateral path; it therefore does not appear to dictate unrealistic or inefficient routing within the terminal area.

Summary of Operational Results

The following summarizes the conclusions relating to the safety and pilot acceptability of the RNAV two-segment approach procedure.

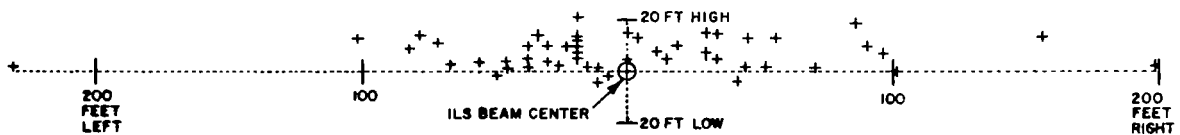
1. The RNAV two-segment approach is a safe and pilot acceptable procedure which does not require unusual piloting skills provided:
 - a. Its limitations in icing and tailwinds are applied in establishing the conditions under which it would be used.
 - b. The crews are familiar with basic RNAV concepts and are qualified to operate the RNAV system.
 - c. Minimums are based upon the approach accuracy consistently attainable for the runway.
2. The two-segment procedure impacts cockpit activity but not to a degree that affects safety. In the DC-8-61 proper entry airspeed and initial configuration are important because of the aerodynamic cleanliness and drag-programming constraints of the aircraft.
3. The RNAV/ILS is an acceptable procedure for use in instrument weather conditions, and may eventually be acceptable to Category II minimums.
4. The RNAV/RNAV is a non-precision approach usable to minimums comparable to other non-precision approaches. The lateral accuracy of the system evaluated would preclude its use for parallel runway operations.
5. The vertical guidance and distance to touchdown provided in the RNAV/RNAV approach are preferable to the unguided descent to MDA/timing methods used in current non-precision approach procedures. It is preferable to the "keep 'em high" procedure currently in wide use in visual conditions because of the vertical guidance and profile standardization it provides.
6. Re-programming the RNAV system to maintain full guidance in the random vector/descent pre-approach environment is unacceptable. A pilot acceptable system must include a simple departure-from and return-to plan capability.

SYSTEM PERFORMANCE

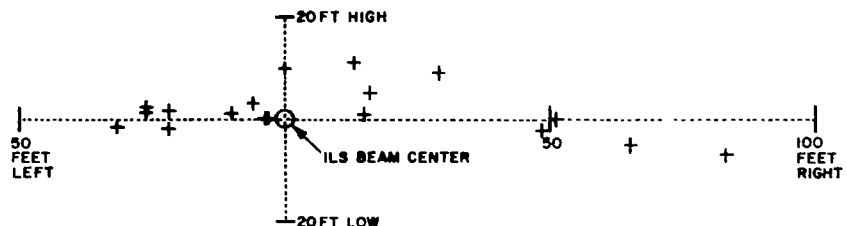
RNAV/ILS Precision Approach Accuracy

The RNAV/ILS approaches are consistently accurate, precision approaches. These approaches should eventually be acceptable to Category II minimums, based on additional experience and demonstration of equipment reliability. This accuracy is attained by using the existing ILS signals and stabilizing the aircraft on the glide slope and localizer by 500 feet above touchdown. The only difference of the RNAV two-segment guidance from the standard ILS guidance during the last 1.5 n. mi. of the approach is that gain programming is based on RNAV distance to touchdown data rather than a time-based function.

Although in-service approaches were limited to actual ceiling minimums of 500 feet, 51 approaches were flown down to 200 feet radio altitude and 17 were flown down to 100 feet radio altitude in visual conditions with the autopilot engaged. Figure 6 shows the location of the aircraft with respect to the ILS beam center for these approaches. At 200 feet all 51 approaches were within 23 feet above and 5 feet below glide slope. The bias to the high side of the glide slope is discussed in the Autopilot Performance Section (Page 38). At Category II minimums the autopilot placed all 17 approaches within 11 feet above and 7 feet below glide slope. The Category II window is plus or minus 12 feet.



(a) 200 feet radio altitude - 51 approaches



(b) 100 feet radio altitude - 17 approaches

Figure 6 - Aircraft Position versus ILS Beam Center
Data from In-Service Evaluation RNAV/ILS Approaches
Note that scale of 6b is twice that of 6a

The only major difficulties encountered with RNAV/ILS approaches were related to the capture of the localizer. It had been originally intended that the switch from RNAV (VOR-DME navigation) to the localizer would occur over a period of time during which localizer, VOR, and DME would all be used by the RNAV system to make a position estimate. For a number of technical reasons this was found to be impractical. The system was ultimately designed to switch instantaneously from RNAV lateral control to standard flight director and autopilot localizer tracking when within 1.5 dots* of the localizer and "Upper" was the next waypoint. After the RNAV roll output to the autopilot was optimized, 90° intercepts of the localizer at 200 knots without appreciable overshoot were demonstrated using this system. The accuracy of the standard localizer tracking systems as shown in Figure 6 is also acceptable for approaches to low weather minimums.

Pilot opinion confirmed that the RNAV/ILS was a good precision approach. The consensus among guest pilots in the out-of-service evaluation was that although conservative minimums should be used initially, the approach could eventually be used to lower minimums. Minimums recommended by the participating pilots are summarized in the tables on page 26. Although system accuracy and performance is acceptable at decision height for Category II weather minimums, the profile developed does not comply with the existing FAA requirement that Category II approaches be stabilized on the glide slope by 700 feet AFL.

RNAV/RNAV Non-Precision Approach Accuracy

One-hundred seventy-six RNAV/RNAV approaches were flown during the program, 128 out-of-service and 48 during the In-Service Evaluation. These approaches were made to 24 runways at 15 airports. The accuracy of these approaches varied from runway-to-runway and from day-to-day at a given runway. RNAV/RNAV approaches are non-precision approaches, requiring minimums similar to other non-precision approaches. This is primarily because lateral (cross-track) errors can position the aircraft off the runway centerline. Due to the 5.5° flight path angle on the upper segment, along-track errors of the same magnitude result in upper segment altitude

* Dots are units of angular deviation. For ILS and two-segment deviation displays, 1 vertical dot is .35°, 1 lateral dot is approximately 1°.

errors less than 1/10 the magnitude of cross-track errors. Pilots were favorably impressed with the vertical guidance available on RNAV/RNAV approaches. This is a desirable feature not presently available in non-precision approaches. However, the lack of accuracy and repeatability with respect to lateral positioning result in recommended minimum ceilings of 500-1000 feet, such as are typical for non-precision approaches.

The factors which affect the accuracy of RNAV/RNAV approaches are the type (VOR and/or DME) and geometry of nav aids available for the approach, and the quality of the signals from the nav aids as they are affected by range, topography, and transmission quality. As a result, operating minimums must be set on an individual runway basis and may be expected to vary widely.

The evaluation of RNAV/RNAV approaches in this program was complicated by the fact that the cross-track steering gain was not optimized in the system used. A shear in the crosswind component on an approach would result in a significant standoff from the desired RNAV lateral track (Figure 7). The mean standoff at system disconnect (approx. 1.8 n. mi. from touchdown) was 1 dot. This tracking error could either add to or reduce the displacement from the runway due to navigation errors. Another complication was errors in the

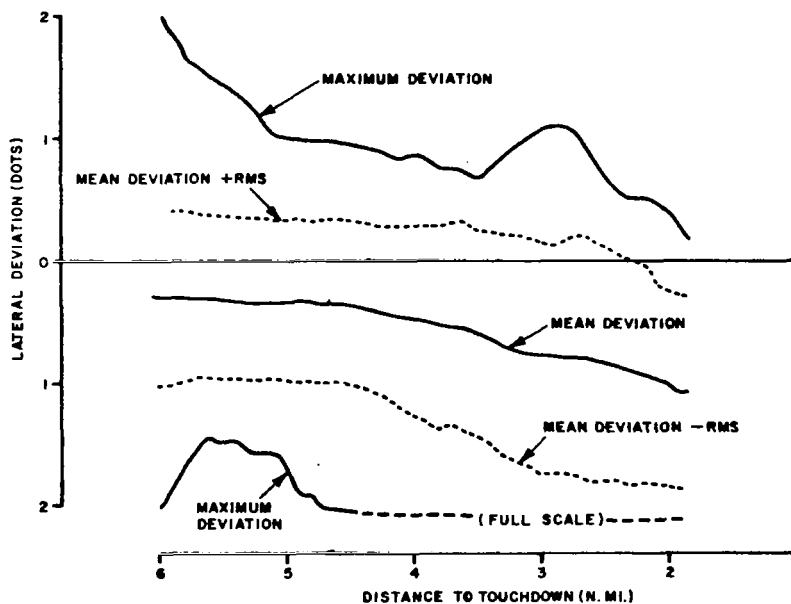


Figure 7 - Lateral Tracking Performance on RNAV/RNAV Approaches
Data from 37 RNAV/RNAV Autopilot Approaches. Standoff is due to insufficient steering gain. Bias to the right is because most RNAV/RNAV approaches were made to the south or south-west with crosswind component primarily from the west.

RNAV data base, i. e. the stored latitude and longitude of waypoints. Although gross data base errors were easily noted in flight checking approaches before they were used by line pilots in regular line service, small errors could be masked by the basic RNAV accuracy. This was the case at Los Angeles and Las Vegas, where errors of .1 or .2 arc-minutes in latitude or longitude were not discovered until after the evaluation was completed. In spite of these problems, sufficient experience was obtained at several runways to draw conclusions about the acceptability of RNAV approaches (two-segment or otherwise) based on subjective comments by pilots and observers.

At both airports used during the out-of-service evaluation, Stockton and Pueblo, the primary navaid was positioned near (but not on) the upper segment of one of the approaches. Those approaches which passed over the navaids (SCK 29R and PUB 25R) did not demonstrate the level of repeatability noted on the approaches which were headed towards the navaid for the entire approach. The navaid on the Pueblo Runway 25R approach is only 2.1 n. mi. from the end of the runway. When passing nearly directly over the transmitter, the radios would be invalid for a period of time, and the system would automatically disconnect if they were invalid for 15 seconds. Approaches with similar navaid configurations should be evaluated carefully to avoid nuisance system disconnects.

At Cleveland and Milwaukee the primary navaids were 15 and 20 n. mi. respectively from the field. Accuracy at these airports was satisfactory for non-precision approach minimum ceilings of 800-1000 feet. Although a DME was collocated at the glide slope at Cleveland, VOR-DME navigation based on the primary navaid alone was used due to the geometry constraints of DME-DME navigation, i. e. it is not used when the stations are within 30° bearing of or opposite each other relative to the aircraft position. At Milwaukee, DME-DME navigation was used, the second DME station being about 45-50 n. mi. away.

The effects of unacceptable navaid quality were demonstrated during the evaluation of approaches to Bradley Field, Windsor Locks, Conn. The two navaids available for approaches to Bradley are both very noisy at approach altitudes due to their distance from the airport and the intervening topography. Navaid geometry is such that DME-DME navigation is used on the upper segment of the RNAV/ILS approach to one runway but VOR-DME is used throughout the RNAV/RNAV approach to the opposite runway. The navaid noise is of such a magnitude that it is not filtered by the normal RNAV system averaging functions. On RNAV/RNAV approaches VOR noise resulted in a shift of the upper segment position towards or away from the runway which appeared in the cockpit as unacceptably erratic vertical guidance. Note that if equally noisy VOR stations were located along or near the runway centerline, RNAV/RNAV lateral guidance would be affected but RNAV/ILS approaches

would not be affected since localizer is used for lateral guidance.

Effect of RNAV Accuracy on Profile Geometry

RNAV accuracy should be considered in the specification of RNAV two-segment profile geometry, whether or not the approach interfaces with an ILS. The upper segment intersected the glide slope at 575 feet AFL to allow consistent stabilization on the lower segment by 500 feet AFL. However, this stabilization criteria would not be met if the upper segment is shifted towards the runway due to RNAV inaccuracies.

In order to assess the accuracy with which upper could be established, 56 in-service approaches to Los Angeles International Airport were analyzed. It was found that on the average, the upper segment intercepted the ILS glide slope at 672 feet, with an RMS about the average of 76 feet. The average glide slope intercept was 97 feet higher than expected. This bias error has been attributed in part to an error in the basic ANS 70 A navigation equation which has since been corrected by Collins. Based on simulation studies, Collins has shown that with the corrected navigation equations the bias error would be significantly reduced.

Autopilot Approach Performance

The autopilot performance in tracking the desired two-segment vertical path was excellent. Figure 8 is the result of a statistical analysis of 139 In-Service Evaluation approaches. The discontinuity at 2.25 n. mi. in Figure 8 (and in Figure 9 on the next page) is due to the switch of the HSI vertical deviation scale from referencing upper segment to referencing glide slope. This discontinuity represents the initiation of the transition to the glide slope, and not a deviation from the desired track.

Both RNAV/RNAV and RNAV/ILS approaches are included in the upper segment data in Figure 8, but only 69 RNAV/ILS approaches to 3° glide slopes are included in the lower segment data. The data was normalized to the Los Angeles profile such that the "Upper" waypoint is at 8 n. mi. from touchdown and glide slope capture of all the approaches occurs 2.25 n. mi. from touchdown. The analysis includes data from approaches to 20 different runways at 11 airports. Fifty of the approaches used in this analysis were to Los Angeles Runway 25L.

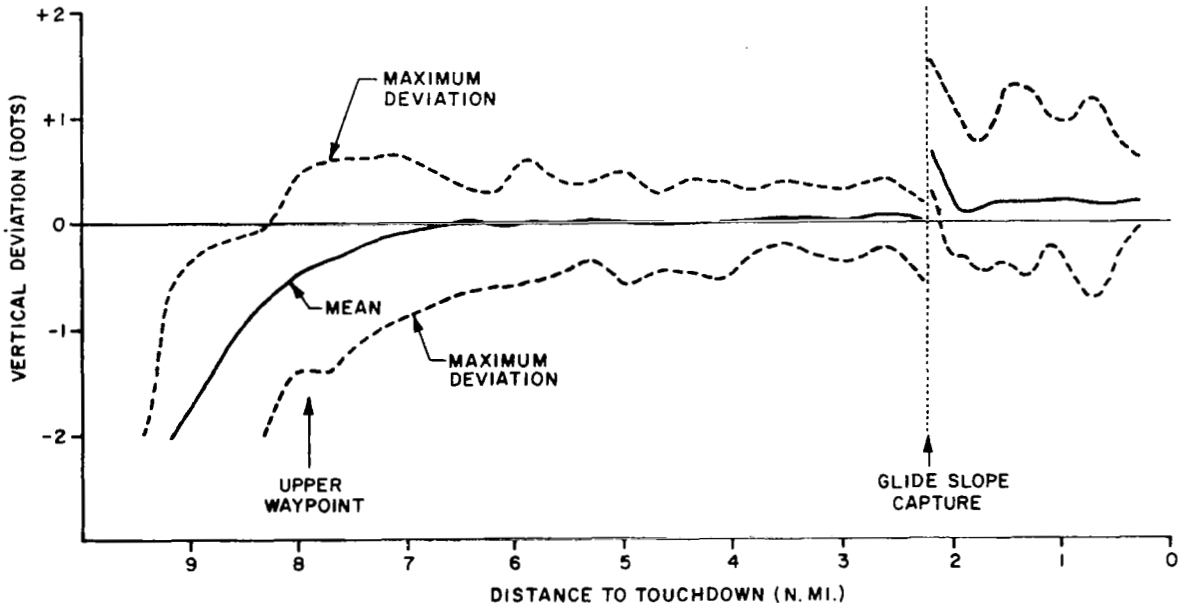


Figure 8 - Autopilot Vertical Tracking Performance
Data from 139 In-Service Evaluation Approaches

Upper segment capture nominally occurs about .75 n. mi from "Upper". On the average the transition lasted 2 n. mi., and the aircraft was on the upper segment by 6.75 n. mi from touchdown, 700-800 feet below the initial approach altitude. The maximum overshoot experienced was .6 dot. Tracking of the upper segment was excellent, the average deviation was less than .05 dot. The maximum tracking errors experienced were about .5 dot; the root-mean-square of the tracking error was .1-.2 dot.

Glide slope capture occurs when the aircraft is about 2/3 dot above the glide slope. The transition is completed in about .4 n. mi., but there is a standoff above the glide slope of less than .2 dot for the remainder of the approach. The flight crews and RNAV observers did not mention this slight standoff, but it could be eliminated by careful optimization of the glide slope capture software in the RNAV system.

Flight Director Approach Performance

Flight director and pilot performance in tracking the vertical path was not as good as the autopilot performance, but was generally satisfactory. Figure 9 is the result of analysis of data from 44 approaches during the In-Service Evaluation. This data was normalized to the Los Angeles approach profile in the same way as the data for Figure 8 was normalized.

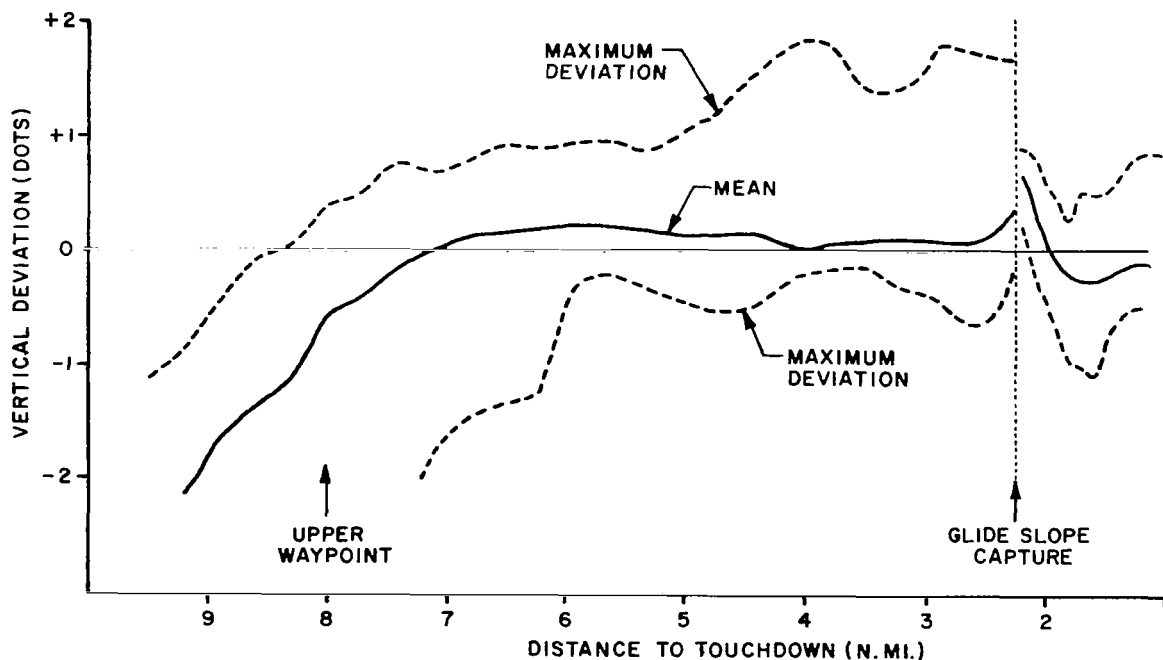


Figure 9 - Flight Director Vertical Tracking Performance
Data from 44 In-Service Evaluation Approaches

Pilots kept the pitch commands within 1 degree of null on the average. The average overshoot of the upper segment was 1/4 dot, and on some approaches the deviation from the upper segment was as much as 1.8 dots high. It had been noted in out-of-service flying that the flight director pitch down commands were not aggressive enough in high ground speed situations to return the aircraft to the upper segment if the aircraft was above it. The pitch command gains were never optimized to improve this performance. As a result, satisfactory flight director approaches required close attention to the pitch commands by the pilot to avoid drifting above the upper segment. On three In-Service Evaluation flight director approaches automatic disengagement was experienced upon reaching the minimum distance to touchdown without having captured the glide slope due to the lack of flight director aggressiveness when above the upper segment.

On the average, the lower transitions resulted in dipping below the glide slope at this point by 0.3 dot (19 feet). However, guidance was returning the aircraft to the glide slope when the pilot stopped following the commands to complete the approach visually. Like the .2 dot autopilot standoff, this performance was not mentioned by flight crews or observers, but evident upon statistical analysis of the approaches. Flight director glide slope capture performance could be improved by optimizing the lower transition RNAV software.

Airspeed and Power Control

Figure 10 shows the average airspeed and power settings, and the distribution of configuration scheduling used during 169 In-Service Evaluation approaches.

The landing gear was down prior to the upper segment capture point on 75% of the approaches and was lowered during the upper transition on the remainder of the approaches. Full flaps were selected when first on the upper segment as recommended on about 75% of the in-service approaches. On the remaining approaches the flaps were lowered to 50° closer to touchdown, thereby providing additional noise abatement. However, analysis of individual approaches did not indicate that excessive airspeed or the flap blow-back feature of the DC-8 was the reason for delaying selection of full flaps.

The upper transition was typically entered with the aircraft decelerating through 170-165 knots with the throttles set at 3000 pounds per hour (pph) fuel flow, or about 1.18-1.20 EPR (Engine Pressure Ratio). The throttles were pulled back to about 1800 pph and the airspeed was down to 160 knots prior to "Upper". Idle fuel flow for the JT-3D engines on the DC-8 is about 1000 pph. At an 1800 pph throttle setting the aircraft continued decelerating on the 5.5 degree upper segment at a rate such that the desired upper segment airspeed (averaging about 147 knots) was attained at about 3.75 n.mi. from touchdown, at which point the throttles were eased up to about 2000 pph to maintain the airspeed. An analysis of ten of the approaches which were flown in instrument flying conditions showed that by entering approach at 155-160 knots with the

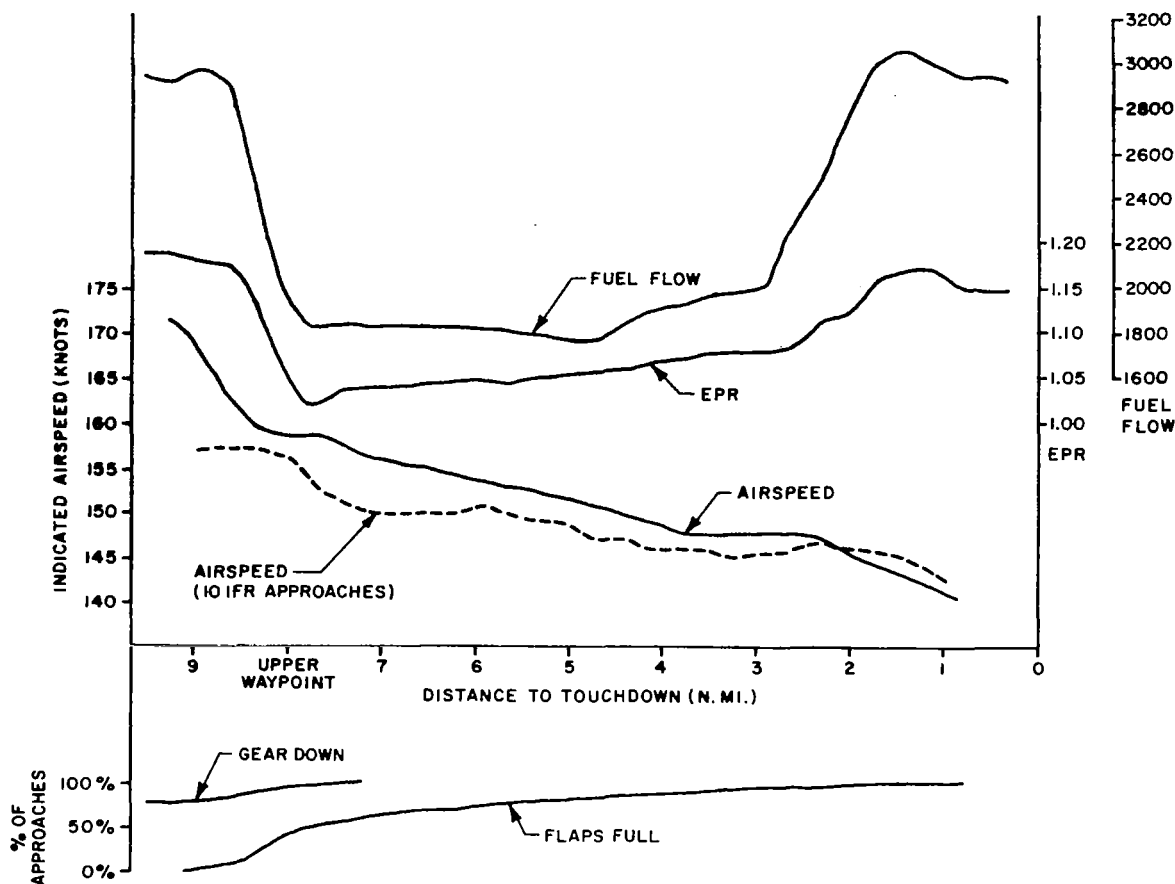


Figure 10 - Airspeed Power and Configuration Control Analysis
Data from 169 In-Service Evaluation Approaches

aircraft fully configured for the approach, crews were able to attain their desired airspeed earlier in the approach and maintain 2000 pph fuel flow throughout the upper segment. Average headwind for these approaches was about 5 knots. Configuration and airspeed control are more critical in the DC-8 than in the B-727. However, it appears from these results that sufficient margins exist in the procedure developed to provide for a fully stabilized approach when conditions require, but to allow judicious departures from a fully stabilized approach to a modified decelerating procedure when conditions allow.

Fuel flow is increased from 2000 pph to 3050 pph steadily through the lower transition. At 1.5 n. mi. from touchdown, 500 feet AFL, the throttles are backed off to about 2900 pph in order to bleed off the 5 knots of airspeed above V_{ref} ($V_{ref} = 1.3V_{stall}$) prior to touchdown. The 3050 pph throttle setting is not higher than normally required to maintain a constant airspeed on the 3° glide slope, and does not indicate that excessive power is applied to assist in completing the lower transition.

RETROFIT COSTS AND SYSTEM MAINTAINABILITY

In addition to determining the flight operational acceptability of the RNAV Two-Segment approach, the impact of installing the equipment on a fleet of aircraft was studied (Ref. 20).

The cost of installing dual special purpose two-segment approach system in UA's B-727-200s had previously been estimated to be \$35,000-\$40,000 (1973 dollars) per aircraft. The cost of adding a two-segment approach capability to dual RNAV systems previously installed on an aircraft would be substantially less than this. If the RNAV systems were designed to interface with the ILS to make standard ILS approaches, the addition of a two-segment capability would cost about \$1500 (1975 dollars) primarily to add approach progress annunciation and for RNAV computer software development. The necessary aircraft modifications would be minor, and could be incorporated without requiring special aircraft out-of-service time. It is assumed the flight crew and maintenance personnel training for the addition of the two-segment approach mode to the RNAV systems could be incorporated in existing recurrent training program, and incremental training costs would therefore be negligible.

The two-segment approach system includes safety protection logic which can disconnect the system during an approach for reasons which may not be readily apparent to the crew. Accordingly, software developed for the two-segment approach should include a maintenance recall capability, to prevent the needless removal of serviceable avionics. Such a capability would provide to the mechanic, and the flight crew if desired, information regarding the cause of system disengagement on the previous approach.

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SUMMARY OF TWO-SEGMENT APPROACHES

	Out-of-Service		In-Service	
	<u>RNAV/ILS</u>	<u>RNAV/RNAV</u>	<u>RNAV/ILS</u>	<u>RNAV/RNAV</u>
Chicago	13	7	9	1
Cleveland			8	11
Denver	8	3	3	4
Las Vegas				10
Los Angeles	4		67	2
Milwaukee			3	3
Newark	12	2	1	
Norfolk			8	9
Pueblo ⁽¹⁾	209	91		
Reno ⁽²⁾	36	7		
Richmond			9	
San Diego			2	
San Francisco ⁽²⁾	35	4	6	
Seattle	8	6	2	1
Stockton ⁽²⁾	423	37		
Vancouver	4	2		
Washington			8	7
Windsor Locks			6	
Totals	<u>752</u>	<u>159</u>	<u>132</u>	<u>48</u>
	911		180 ⁽³⁾	

Notes:

- (1) Includes Guest Pilot Evaluation (120 RNAV/ILS and 60 RNAV/RNAV)
- (2) RNAV/ILS Out-of-Service totals include Phase I (non-RNAV) Two-Segment Approaches as follows: Reno-20; San Francisco-22; Stockton 220.
- (3) Includes 18 approaches flown by Flight Managers.

LIST OF OUT-OF-SERVICE EVALUATION PILOTS

Project Pilot Team

Gordon Brown, UA Manager DC-8 Flight Operations Development
Bill Brown, UA Project Pilot
Fred Drinkwater, NASA Project Pilot
Hugh Monteith, UA Project Pilot
John Morrison, UA Lead Project Pilot
Hal Snyder, UA Project Pilot
Bob Stimely, UA Manager B-727 Flight Operations Development

Test Pilots

FAA

Jim Bugbee, Engineering Pilot
Judge Reynolds, Flight Standards Pilot

Guest Pilots

FAA

** Oscar Berge, Air Carrier Operations Specialist
* Harry Langdon, Operations Inspector
** Lynn Mayfield, Principal Operations Inspector
** Ralph Noltmeier, Chief, Flight Technical Programs Staff
** Dick Scully, Director of Environmental Quality

American Airlines

Frank Nehlig, Flight Manager
Al Reeser, Director of Flight Engineering

Continental Airlines

Lee Lipsky, Line Pilot
Carl Rogers, Assistant Flight Manager

Delta Airlines

R. A. Byrd, Manager Flight Operations
Francis McDowall, Manager Flight Operations

Eastern Air Lines

Charles Tennstedt, Manager of Flying

Flying Tiger Line

Dick Keefer, Assistant Manager of Flying

National Airlines

Roy Berube, RNAV coordinator

Northwest Airlines

Don De Bolt, Fleet Manager, B-727 and B-707

LIST OF OUT-OF-SERVICE EVALUATION PILOTS

Guest Pilots - continued

PSA

David Ferrell, Captain
Lowell Henderson, Captain

Western Air Lines

Dixon Carter, Regional Manager - Flight

United Airlines

- * Charlie Beck, Training Manager
- * Bob Collins, Vice President, Engineering
- * Ernie Maulsby, Flight Manager
- ** Howard Mayes, Vice President, Flight Technical Services
- * Lyle Reynolds, Flight Manager - Standards
- Lloyd Treece, Vice President, Central Division Flight Operations

Air Line Pilots Association

- Ralph Baxter, Western Airlines Line Pilot
- O. M. Cockes, Eastern Air Lines Line Pilot
- W. P. Crowley, National Airlines Line Pilot
- T. G. Foxworth, Pan American World Airways Line Pilot
- Joe Harris, Trans World Airlines Line Pilot
- ** Ray Lahr, United Airlines Line Pilot
- R. N. Rockwell, Northwest Airlines Line Pilot
- R. V. Studer, Delta Air Lines Line Pilot
- Gene Whitsitt, Braniff International Airways Line Pilot

Manufacturers

- Boeing Airplane Company
 - Brien Wygle, Director Flight Operations
- Lockheed Aircraft
 - A. W. LeVier, Associate Director-Flight Operations Branch
- McDonnell Douglass Corporation
 - George Jansen, Chief Engineering Test Pilot

- * Indicates Guest Pilot participated in Phase I (non-RNAV) evaluation only.
- ** Indicates Guest Pilot participated in both Phase I and Phase II evaluations.
All other Guest Pilots participated in the Phase II evaluation.

MEASUREMENT UNITS

NASA policy, as enunciated in Policy directive NPD 2220.4 dated September 14, 1970, is that measurement values employed in NASA Contractor Reports shall be expressed in the International System of Units (SI). The subject matter of this report, however, pertains to a field in which SI is not the currently accepted standard. In the interest of assuring that material herein is clear and useful to those in the air transportation industry, conventional units for altitude, distance, and airspeed appear in this report. The following scales are provided to convert these units to SI. Several specific values used in this report (*) are explicitly converted for quick reference.

